NATIONAL CENTRE FOR RESILIENCE

Mitigating Landslides Impact in Scotland - MLIS

Summary report

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List of acronyms

ALMEO - Automatic Landslide Mapping with Earth Observation Data

BGS – British Geological Survey

DFT – Department for Transport

DLHA - Daily Landslide Hazard Assessment

MLIS - Mitigating Landslides Impact in Scotland

NLD - National Landslide Database

SU – Slope Unit

Executive Summary

A plain language, concise summary of your findings.

This text is a report of the activities conducted under the Mitigating Landslides Impact in Scotland (MLIS) project. The project was led by the British Geological Survey (BGS) and included the University of Glasgow and the University of Twente (Netherlands). MLIS allowed to update the BGS landslides database and produce a new and novel landslide susceptibility map for Scotland.

Main body

In September 2022 the National Centre for Resilience awarded the British Geological Survey (BGS) funds for the Mitigating Landslides Impact in Scotland (MLIS) project. MLIS is a collaboration with University of Glasgow and the University of Twente (Netherlands) and aims at combining a novel landslide susceptibility model with elements-at-risk to support emergency services and landslide hazard mitigation strategies in Scotland.

The project was carried out between September 2022 and March 2023 and in order to achieve the objectives, the following activities have been organised:

1) Updating the current landslide inventory map of Scotland.

2) Producing a new landslide susceptibility model.

3) Defining guidelines for generating a landslide exposure model for critical transportation infrastructure.

4) a workshop in Glasgow.

In the following text we are going to details the rationale behind the MLIS project, the work behind each of these objectives, the results achieved and future plans of activities to build on MLIS..

Introduction

This project aims to create a bias-reduced predictive spatial statistical model, combining it with elements at risk and derive an exposure model. The latter is crucial for a better understanding of landslide risks, long term planning and disaster management during emergencies.

Landslides in Scotland threaten critical infrastructure and human lives. A key information to reduce landslide risk consists of an accurate landslide inventory. However, Scottish inventory maps are incomplete because most landslides are mapped along roads or whenever a citizen reports them and in sparsely populated regions slope failures can go therefore underreported (Figure 1). With more than 34% of Great Britain landmass, Scotland only records ~13% of the total landslides mapped out of ~18,000 in the BGS National Landslide Database (BGS-NLD, accessible at https://www.bgs.ac.uk/geology-projects/landslides/national-landslide-database/).

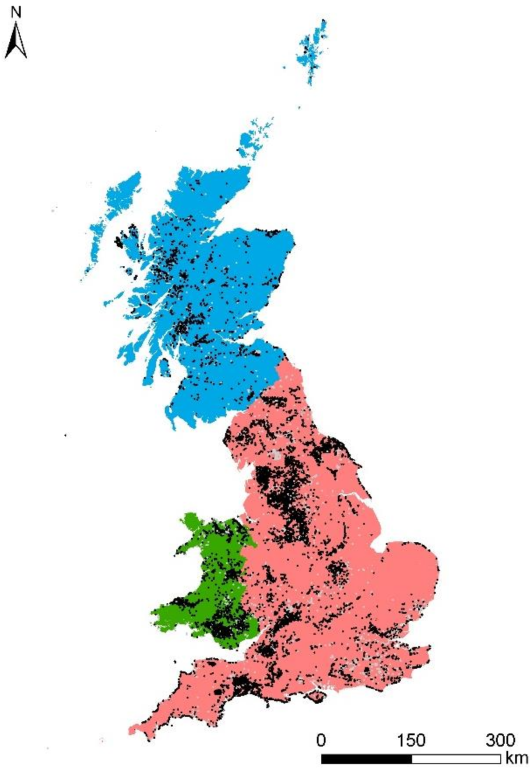

FIGURE 1 - SPATIAL DISTRIBUTION OF LANDSLIDES ACROSS GREAT BRITAIN.

The British Geological Survey uses the current Scottish inventory to develop its landslide susceptibility model (GeoSure - landslides), which is used by policymakers and spatial planners to assess and mitigate landslide risk. There is a need to improve GeoSure since it is spatially biased towards densely-populated areas where most of the reports are, inevitably, coming from.

Moreover, GeoSure is solely based on expert knowledge of the terrain (geomorphology and geology). Given the latest developments in artificial intelligence and predictive tools, a combination of expert-based, statistical, and computationally efficient modelling techniques will advance the existing landslide susceptibility model. Ultimately, the current model has never been used in conjunction with the elements-at-risk to study how we can integrate the exposure component.

Updating the BGS NLD

BGS is currently working on a methodology for automatically mapping landslide events from satellite data. The project is called ALMEO (Automatic Landslide Mapping with Earth Observation Data) and is funded through the BGS International NC programme 'Geoscience to tackle Global Environmental Challenges', (NE/X006255/1). We used a preliminary version of the tool which builds on the NASA's Sudden Landslide Identification Product (SLIP[1]). A total of 31 landslides (debris flows) has been

[1] Fayne, J.V., Ahamed, A., Roberts-Pierel, J., Rumsey, A.C. and Kirschbaum, D., 2019. Automated satellite-based landslide identification product for Nepal. Earth Interactions, 23(3), pp.1-21. https://doi.org/10.1175/EI-D-17-0022.1

added, so distributed: 8 from Rest and Be Thankful occurred in October 2018 and/or August 2020, 20 from Glengyle and occurred in August 2019 and 3 from Askival occurred in April 2022 (Figure 2).

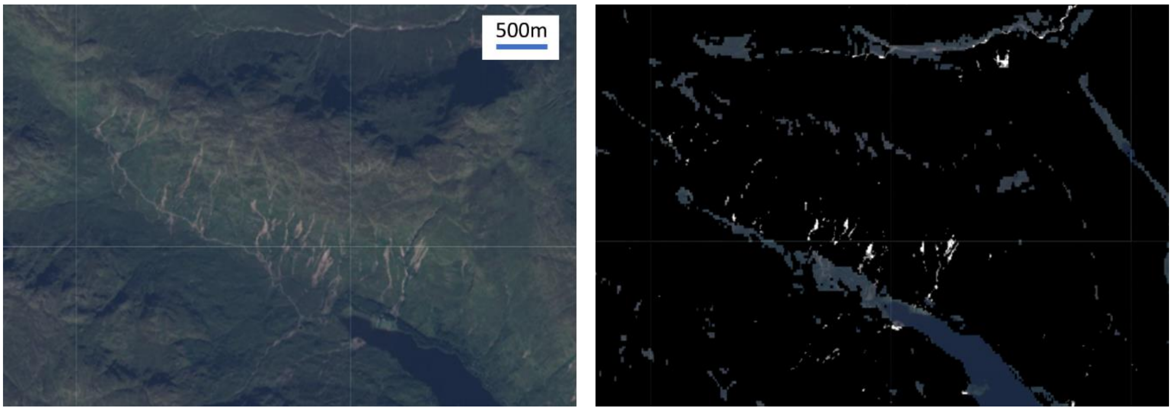

FIGURE 2 - A SENTINEL-2 IMAGE ACQUIRED OVER GLENGYLE IN SEPTEMBER 2019 (LEFT) AND LANDSLIDES IDENTIFIED WITH ALMEO AS WHITE POLYGONS (RIGHT).

These additional inputs have been included into a new landslides inventory map for debris flows which does include also other events still not reported in the BGS NLD. The total amount of debris flow used for the susceptibility model is 1,854..

Susceptibility Model

This is the core section of the MLIS work. The updated landslide inventory, as described in the previous section, has then been ingested into a Bernoulli model to assess landslide occurrence per areal slope unit (SU). The model has been implemented by Erin Bryce, a PhD student at the University of Glasgow who has recently applied it for landslides hazard assessment in Dominica[2]. Only debris flow events have been used since they represent the major landslide threat to people and infrastructure in Scotland.

The model detects areas of higher landslide susceptibility and distribution, namely the probability of observing a landslide in a SU using a Bernoulli distribution. We work at SU level rather than pixel level since SUs suitably approximate the morpho-dynamic behaviour of landslides in general, debris flows in this case. Indeed, a SU encompasses the geographic space between ridges and streamlines, roughly represented as half basins of a given order extracted by maximising areas with homogenous aspects[3]. A total of 153,282 SUs has been retrieved for Scotland.

The observations (presence/absence for the Bernoulli likelihood) are assumed to be conditionally independent given a Gaussian latent process that drives the trends, dependencies and non-stationary patterns observed in the data. The latent process is characterised by a linear predictor with a flexible additive structure allowing the incorporation of covariates and spatial effects. Specifically, we rely on

[2] Bryce, E., Lombardo, L., van Westen, C., Tanyas, H. and Castro-Camilo, D., 2022. Unified landslide hazard assessment using hurdle models: a case study in the Island of Dominica. Stochastic Environmental Research and Risk Assessment, 36(8), pp.2071-2084. https://doi.org/10.1007/s00477-022-02239-6

[3] Amato, G., Eisank, C., Castro-Camilo, D. and Lombardo, L., 2019. Accounting for covariate distributions in slope-unit-based landslide susceptibility models. A case study in the alpine environment. Engineering geology, 260, p.105237. https://doi.org/10.1016/j.enggeo.2019.105237

generalised additive models (GAMs) to flexibly model the covariates' influence using fixed and random effects, which are also known as linear and non-linear effects in terms of their influence.

The covariates ingested in the model are detailed in Table 1 and have been extracted as mean/median within each SU.

TABLE 1 - MAIN INFORMATION ABOUT THE COVARIATES USED IN THIS WORK.

Variable	Type	Units	Scale or Resolution	Source
Debris flow inventory	Binary response	0 = absence, 1 = presence	N/A	National landslide database and addition through ALMEO
SU area	Continuous explanatory	m^2	50m and 5m	DTMs: NextMap DTM 2007, BlueSky 2014/15
Linear relief within 100m buffer	Continuous explanatory	adimensional	N/A	extracted from the DTM
Slope mean and Standard Deviation	Continuous explanatory	Degrees	N/A	extracted from the DTM
Precipitation mean and maximum	Continuous explanatory	mm	1000m	MetOffice HadUK-Grid Gridded climate observations, 1999-2019.
Profile curvature mean and SD	Continuous explanatory	1/m	N/A	extracted from the DTM
Planform curvature mean and SD	Continuous explanatory	1/m	N/A	extracted from the DTM
Quaternary domain	Categorical explanatory	Unit-less	from 1:10,000 to 1:1,000,000	BGS quaternary domains
Superficial deposit	Categorical explanatory	Unit-less	1:625,000	BGS geology
Bedrock	Categorical explanatory	Unit-less	1:625,000	BGS geology

We have extended the susceptibility model by incorporating the count of debris flows within each SU. This was done by modelling the debris flows as a log-Gaussian Cox process, providing a more accurate measure of debris flow intensity per SU across Scotland. We stress again that we assume that the observations (presence/absence of a debris flow) are conditionally independent given a latent

Gaussian structure that drives the trends, dependencies and non-stationary patterns observed in the data.

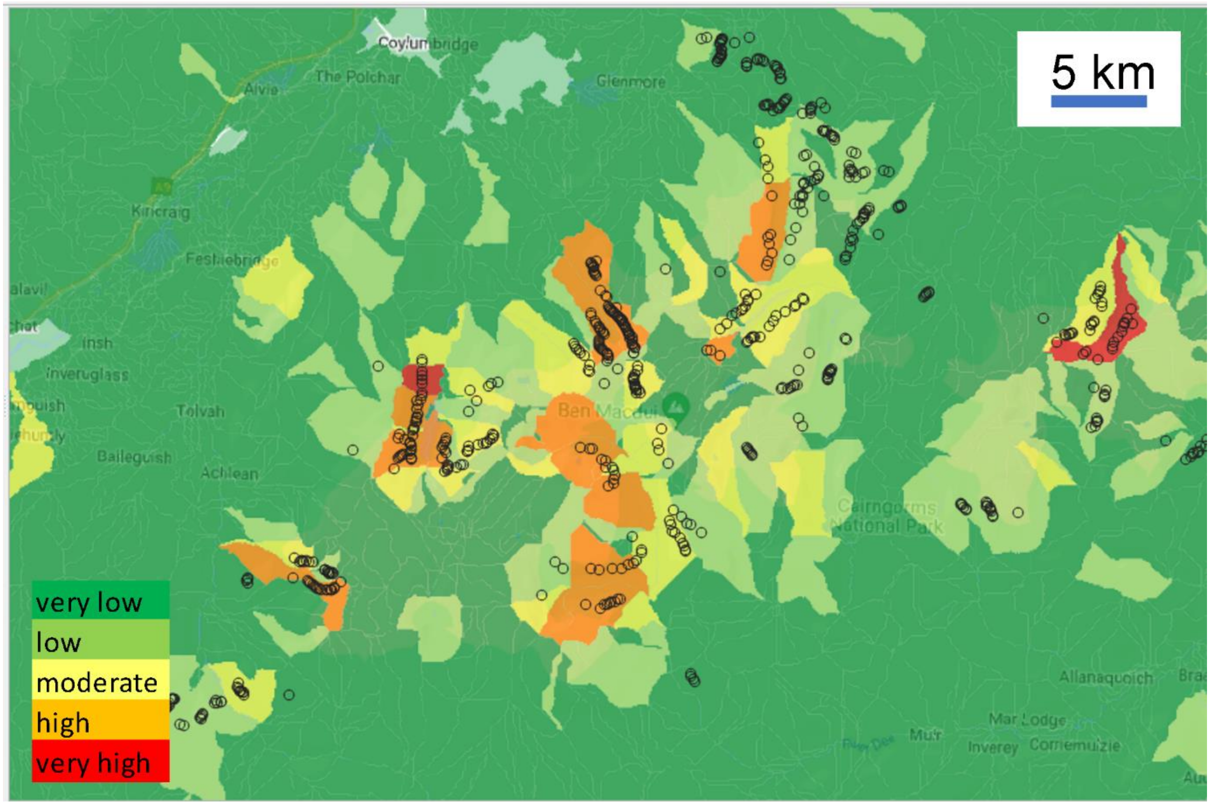

FIGURE 3 - SUSCEPTIBILITY LEVELS OVER BEN MACDUI

Spatial dependence between locations is characterised using a Gaussian Process with Matérn covariance structure. The Matérn family of covariance functions is widely used in spatial statistics due to its flexible local behaviour and interesting theoretical properties (Guttorp and Gneiting 2006; Stein 2012). To allow for fast inference, we use the stochastic partial differential equation (SPDE; Lindgren et al. 2011) approach that provides accurate Markovian representations of the Matérn covariance. Under a Bayesian framework, we assume relatively weak but highly interpretable Gaussian priors for all the model components and hyperparameters involved and fit our model using the integrated nested Laplace approximation (INLA)[4].

Since the Bernoulli distribution is a novel approach for estimating susceptibility levels compared to the existing GeoSure, the MLIS team is now working for publishing these results into a peer-reviewed journal.

Last step of our work is a scoping study on modelling the exposure of transportation network to debris flow hazard in Scotland, according to the new Bernoulli-based model.

[4] Rue H, Martino S, Chopin N (2009) Approximate Bayesian inference for latent Gaussian models by using integrated nested Laplace approximations. J R Stat Soc Ser B 71(2):319–392

Impact analysis

The final activity of MLIS was to define a methodology for a preliminary exposure model for roads and railways, the so-called transport network, under the new Bernoulli-based landslides susceptibility map.

In this section of the project, we explored different geospatial solutions to combine the exposure analysis with information about the potential damage of different road categories to debris flow impact and develop an impact matrix with associated impact thresholds that can be used to inform the Daily Landslide Hazard Assessment (DLHA). Through the DLHA we plan to provide information of which part of the transport network is exposed to debris flow and what can be the disruption in terms of damage, traffic and rerouting.

The spatial distribution of roads (motorways, primary and A-roads) in Scotland was obtained through the Department for Transport (DfT), UK government and the Ordinance Survey. The information includes not just the location but also the type of infrastructure (e.g., urban, rural, private roads) and the corresponding width.

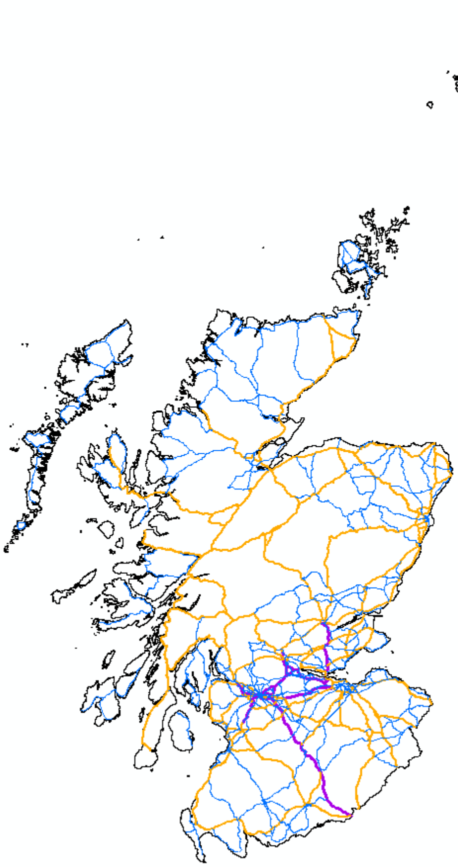

FIGURE 4 - MOTORWAY (PURPLE), PRIMARY ROADS (ORANGE) AND A-ROADS (BLUE) NETWORK IN SCOTLAND.

Conclusions

A 2-day workshop has been organised at the University of Glasgow with the participation of the MLIS staff and stakeholders such as Mark Naylor (University of Edinburgh) and Tanja Waaser (Transport Scotland).

FIGURE 5 - FLYER OF THE MLIS WORKSHOP

The aim of this event was to define the next steps of the collaboration including:

- *exploring further and larger funding opportunities over the next year to upscale the work at UK scale but also to assess the risk, not just the susceptibility.*

- *Publish the novel susceptibility model over the next 6 months and, later on (between the next 2 to 3 years), define and deliver a new methodology for assessing the impact of debris flows on the infrastructure network.*
- *Operational use of this novel methodology for upgrading, over the next 3 to 5 years, current BGS products such as GeoSure.*

Appendix

References

**Referencing in the main body of the report should be included using footnotes*